DOCUMENT RESUME

ED 172 278 CS 502 533

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TITLE A Critical Examination of the Statistic Used for Processing Speech Signals.
PUB DATE Sep 78
NOTE 15p.; Paper presented at the Annual Meeting of the American Psychological Association (86th, Toronto, Canada, August 28-September 1, 1978)

EDRS PRICE MF01/PC01 Plus Postage.
DESCRIPTORS Acoustic Phonetics; *Articulation (Speech); Aural Stimuli; *Cognitive Processes; *Language Processing; Neurological Organization; *Speech Communication; Speech Pathology

ABSTRACT

This paper assesses certain properties of human mental processes by focusing on the tactics utilized in perceiving speech signals. Topics discussed in the paper include the power spectrum approach to fluctuations and noise, with particular reference to biological structures; "1/f-like" fluctuations in speech and music and the functioning of a cerebral cortical field; subjective time and temporal focusing, auditory processing, and speech rate; and J.R. Klauder's phenomenon, with special reference to the "shot noise" case. (Author/PL)

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ED172278

A Critical Examination of the Statistic used for Processing Speech Signals

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ABSTRACT

The paper has the object of assessing certain properties of human mental processes by focusing on the tactics utilized in perceiving speech signals. The nature of the problem is outlined in terms of fluctuations and a model described which is based on the extraction of product elements $\Delta f \times \Delta t$ to form an interaction-sensitive, temporal focusing structure. Support for the mode of operation of the model is provided from data in both auditory and neurophysiological research. Loudness spectra for long samples of English speech exhibit "1/f-like" fluctuations which infer particular kinds of constraints on the growth and decay of spectral energies associated with individual elements $\Delta f \times \Delta t$ within any ensemble of the speech signal. Such loudness spectra are described in terms of two spectral parameters. These spectral parameters are discussed from a cognitive psychophysiological standpoint and certain inferences are drawn concerning the notion of intelligent behavior.

The various arguments may be summarized under the following heads:

(1) The power spectrum approach to fluctuations and noise, with particular reference to biological structures.
(2) "1/f-like" fluctuations in speech and music and the functioning of a cerebral cortical field.
(3) Subjective time and temporal focusing, auditory processing and speech rate.
(4) Klauder's phenomenon, with special reference to the "shot noise" case.

* * *

Paper presented before the American Psychological Association 86th Annual Convention, Toronto, Canada, August 28-September 1, 1978.

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American Psychological Association 86th Annual Convention. 28 August to 1 September, 1978, Toronto, Canada. Symposium "Overt Measures of Covert Mental Processes"; Chairman, Dr. F.J. McGuigan. 0900-1150, Wentworth Room, Sheraton Center.

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This paper has the object of assessing certain properties of human mental processes by focusing on the tactics utilized in perceiving speech signals. The nature of the problem is outlined in terms of fluctuations and a model described which is based on extraction of product elements $\Delta f \times \Delta t$ to form an interaction-sensitive, temporal-focusing structure. The model has support for its mode of operation from data in both auditory and neurophysiological research. Loudness spectra for long samples of English speech exhibit "1/f-like" fluctuations which infer particular kinds of constraints on the growth and decay of spectral energies associated with individual elements $\Delta f \times \Delta t$ within any ensemble of the speech signal. Such loudness spectra are described in terms of two spectral parameters, which are discussed from a cognitive psychophysiological standpoint and certain inferences drawn concerning the notion of intelligent behavior. The arguments can be summarized under the following heads:

Fluctuations and noise
The power spectrum approach
Noise in biological structures
1/f fluctuations in speech and music
1/f and cortical functioning
A cerebral cortical field
Subjective time and temporal focusing
Auditory processing of tonal pulsed sounds
Auditory patterning and speech rate
Klauder's Phenomenon
The "shot noise" case
Concluding remarks

FLUCTUATIONS AND NOISE

Spontaneous deviation from some average regime is a universal phenomenon of molecular origin and in a system with many degrees of freedom, these fluctuations are always present. In non-equilibrium structures they play a crucial role near points of instability, due to a non-vanishing probability that an unstable region may be reached as a result of fluctuation. When an unstable region is reached, certain of the fluctuations become amplified and drive the system to a new ordering principle, or regime. In this region of instability the formation of a fluctuation of a given type is fundamentally a stochastic process and the evolution of new order has an essentially statistical character (*cf.* Glansdorff & Prigogine 1971; Nicolis & Prigogine 1977).

Noise fluctuations generated by identical unitary events, for which the occurrence of any event is independent of previous events, were grouped together under the term "shot noise" in a classic analysis by Rice (1945). Traditionally noises have been divided into equilibrium and non-equilibrium processes. Non-equilibrium noises include shot noise, "1/f-like" noise, and burst noise. The granular nature of current is a source of shot noise and this phenomenon can be expected in any system where the current is carried by non-interacting or moderately interacting carriers. Burst noise consists of irregularly occurring and usually asymmetric phenomena. Of "1/f-like" noise, more later. Thermal noise arises as a result of the grainy structure of the thermal environment and was long considered to be the only source of equilibrium noises. This thought was challenged by the measurements of Voss & Clarke (1976a; 1976b), who produced evidence that "1/f-like" behavior in small semiconductor and metal films in thermal equilibrium arises from equilibrium temperature fluctuations, which modulate the resistance and result in resistance fluctuations.

THE POWER SPECTRUM APPROACH

The power spectrum is an extremely useful way of characterizing the average behavior of any quantity which varies in time and this method is most often used for the analysis of random signals, or noise. Many physical quantities exhibit a power spectrum which varies approximately as the inverse of frequency over many decades of frequency, and such a spectrum is known as "1/f-like". The observed spectra have frequency dependences f^{-n}, where the exponent is constant over a very wide frequency range, say from 10^{-2}Hz to 10^{5}Hz. The exponent 'n' is usually close to unity although deviations of the order of 0.1 have been reported. In the high frequency range of 10^{3}Hz

to 10^6Hz the 1/f noise usually disappears in the white thermal noise of the sample being examined. No flattening in the low frequency range has ever been observed. Investigations into the statistical properties of "1/f-like" noise have a long tradition, but controversy continues regarding which properties are essential. The 1/f spectrum implies that some correlation exists in these fluctuations over all time scales corresponding to the frequency range for which the power spectrum is "1/f-like". References to the widespread occurrence of "1/f-like" fluctuations in the physical world are to be found in a number of reviews (*cf.* Mandelbrot & Wallis 1969; van der Zeil 1970; Hooge 1972). Current and/or voltage fluctuations with power spectral densities which vary in a "1/f-like" manner have been shown to be quite a general phenomenon affecting many systems away from thermodynamic equilibrium (*cf.* Corti & Wanke 1975).

NOISE IN BIOLOGICAL STRUCTURES

Generation of noise is one of the main features of biological membranes. Many different noise components exist, each with its particular spectral properties and dependences on membrane potential, current intensity, channel system or ionic species. Verveen & DeFelice (1974) have given a comprehensive review of noise in vertibrate nerve membranes and nerve fibers. The components which can be measured almost always reduce to "1/f-like" noise in combination with one or more relaxation noise components (*cf.* de Goede *et. al.* 1977). The most important overall observation, as Hooge (1977) stresses, is that ionic conduction exhibits "1/f-like" noise. Indeed, Moolenaar *et. al.* (1976) provided experimental evidence for a direct connection between membrane "1/f-like" noise and simple behavioral effects in a living organism by demonstrating that the "1/f-like" noise fluctuation of a resting membrane could be disturbed and thereby cause the membrane to operate. It was by this means that Moolenaar and his co-workers were able to observe the ciliated protozoan, *Paramecium*, swimming backwards.

1/F FLUCTUATIONS IN SPEECH AND MUSIC

Carrying out long-term measurements of music and speech, Voss & Clarke (1975) showed that the power spectra of loudness fluctuations for many musical selections and for English speech down to a frequency of 5×10^{-4}Hz, were "1/f-like". The pitch fluctuations of music were also shown to have a "1/f-like" power spectrum at frequencies down to the inverse of the length of the piece. Pitch fluctuations of English speech behave quite differently and show a single characteristic time, with a power spectrum that is white

below about 3Hz and which falls off as $1/f^2$ down to about 3Hz. By this means Voss & Clarke established that the average length of an individual speech sound, over a long term, is equivalent to approximately 0.1 seconds. This important result may be interpreted as direct evidence for a measure of average constancy in speech rate. It may also be assumed that a long-term "1/f-like" distribution is an important property of at least English speech. In regard to the highly correlated $1/f^2$ power spectrum for pitch fluctuations of speech, Voss & Clarke explain that the pitches of the individual sounds are unrelated for normal English speech, since the ideas are not related to the pitches but to the meanings attached to the syllables.

1/F AND CORTICAL FUNCTIONING

Gardner (1978), basing himself primarily on the work of Voss & Clarke (1978) and Mandelbrot (1977), remarked that the closer one gets to the brain the closer the electrical fluctuations approach 1/f. He goes on to explain that the nervous system seems to act like a complex filtering device, screening out irrelevant elements and processing only the patterns of change that are useful for intelligent behavior.

I assume that this is the mechanism which Mikhaltsev (1975) refers to as the "dominant". Mikhaltsev explains that the "dominant" is a dynamic constellation of innervated areas in the nervous system which optimizes the reaction to an acting stimulus, or its physical correlate, the dynamics of the steady potential shifts in the cortex. The "dominant" is the mechanism which controls the volume of information perceived out of the whole volume of information available at that moment. Mikhaltsev assumes this physiological mechanism to be equivalent to a narrow filter in the information domain, in which the action of such a filter prevents the overloading effect of memory.

Mikhaltsev (1978) attempted to describe the broad operating principles of engram formation and retrieval directly. He envisages persistent changes of local impedance of cortical tissue induced by flows of current and by electromagnetic fields, as being essential steps in engram formation. These persistent changes of impedance, says Mikhaltsev, are caused by changes in the electrical characteristics of the neural tissue on the molecular level; he receives considerable support here from Schmitt *et. al.* (1976) and Bawin & Adey (1977). Mikhaltsev sees this impedance field as a measure of regional information storage. In other words, the electrical signal is the field of cortical currents, so that for each point of the tissue the Fourier transformation may be applied and the field characterized in spectral or

autocorrelation terms. The whole process of propagation of the signal in the cortex, and of the electromagnetic field which the signal induces, will obey the Maxwell equations along any correctly selected contours and sections.

A CEREBRAL CORTICAL FIELD

From a structural point of view, Mikhaltsev's model is not in conflict with the functional neuron network for the cerebral cortex as described by Szentágothai (1978). Indeed, Szentágothai refers to the emergence of dynamic patterns of largely subthreshold activities resulting from the overlapping between afferent arborizations, which may modify the suprathreshold function of the network by adding some neurons here, or deleting some neurons there, from the active population.

Adey (1977) also presents data showing that slow electrical oscillations occur in cerebral dendrites and thus form a cell-cell communication system that functions independently of a flow of pulses. The behavioral evidence suggests to Adey that these weak oscillating electric gradients which appear in brain tissue, are associated with modification in recall and modification in the sequence of subjective temporal estimates.

Adey is clearly speaking here of a mechanism akin to Mikhaltsev's "dominant". I find extremely interesting Adey's idea of electric gradients being associated with modification in the sequence of subjective temporal estimates.

SUBJECTIVE TIME AND TEMPORAL FOCUSING

Subjective temporal estimation has a huge literature, as Guay & Hall (1977) have shown. However, measurements of subjective time duration carried out by Sagal & Bagrova (1972) and by Eisler (1975) for human subjects, seem finally to establish that subjective time observes a power function. Sagal & Bagrova note the following. "It may be assumed that the higher nervous activity acts as a complex adaptive system with variable characteristics of activity. It is natural to represent the sensory space of the reflexion as a space with a variable metric. In conditions of optimal activity, the sensory metric becomes the simple linear function of the imposed metric of the stimuli". Lunney (1974) described the situation under optimal activity with a test of perceptible time differences in which nothing less than full attention would suffice. He found that the mechanism of time discrimination produces an approximately exponential form with increasing interval. The

limit of discrimination seems to be biologically imposed, says Lunney.

Divenyi (1976) indeed argues that detection of a signal is a stimulus-unspecific response. He is supported in this by Divenyi & Danner's (1976) finding that the spectral composition of acoustic markers has no influence on auditory time discrimination as long as the two markers of a given interval have identical spectra. Divenyi & Danner found that in general the discriminability of a time interval begins to suffer markedly only when shorter than about 25 milliseconds, and then only when either the markers are not clearly audible or the two signals differ excessively in spectra. They did observe a tendency, more completely confirmed in data from subsequent tests, for the bandwidth of their noise-burst markers to influence time discrimination at base intervals shorter than 30 milliseconds, suggesting that the efficiency of an auditory signal to mark time is inversely related to the extent of short-term fluctuations in its power. Diveny & Danner concluded that the perceptual system breaks up sequential auditory information into separate streams which are segregated on the basis of their spectral coherence, with the result that reception of temporal information across these streams is severely degraded.

AUDITORY PROCESSING OF TONAL PULSED SOUNDS

Threshold perception for tonal pulsed sounds was reviewed by Knox & Braminder (1977) and found to depend on the level of background noise and on the product of small changes of frequency and small changes of duration ($\Delta f \times \Delta t$); in other words on the number of waves of the harmonic signal (*cf.* Saprykin & Belov 1968). To be considered as a spectral analyzer the auditory system requires a signal equivalent to several cycles in the zone of maximum frequency sensitivity, although a surprising degree of discrimination is maintained with only half a cycle duration of signal (*cf.* Sipovskii *et. al.* 1972). About 256 harmonic waves are required for the auditory system to achieve maximum discrimination as a spectral analyzer (*cf.* Saprykin & Nikitin 1977), although maximum efficiency of detection is achieved for some 42 waves of the signal (*cf.* Saprykin & Sagal 1972). For short sounds, processing of the signal does not cease at the moment of switching off the signal (*cf.* Samoilova & Zaitseva 1971).

A number of these findings have been confirmed by Santee & Kohfeld (1977) in reaction-time experiments. Their results caused Santee & Kohfeld to speculate that the detection of a signal and a judgement of its loudness may require different perceptual processes.

Naftalin (1977) and Barrett (1978) have made proposals for models of the peripheral hearing mechanism which attempt to explain some of the experimental findings in more theoretical terms.

AUDITORY PATTERNING AND SPEECH RATE

Bradley & Bryant (1978) strongly suggested that an important cause of backwardness in reading ability is difficulty in the perceptual organization of auditory patterns. In this connection it is interesting to consider the results of meter interpretation tests carried out by Oshinsky & Handel (1978). These workers describe a situation where polyrhythmic presentations gave discontinuous reversals in perceived meter with smooth changes of presentation rate, implying that the perceptual organization of auditory patterns in music, and probably speech, must depend in part on the absolute tempo.

The long-term average length of an individual speech sound in English was found by Voss & Clarke (1975) to be approximately 0.1 seconds. On the other hand, Jaffe *et. al.* (1973) indicated that clinicians broadly agree that significant deviations from a normal speech rate, which is more in the nature of a band with upper and lower limits, constitutes a pathological symptom. Jaffe suggests that the unimodal distribution of speech rates seen in normal populations is the outcome of some homeostatic mechanism which maintains an optimum rate and counteracts extreme deviations in either direction. Neurophysiological evidence for the inherent bimodality in neural control of speech rate derives from stimulation of the ventrolateral nucleus of the thalamus in the dominant hemisphere during neurosurgical procedures (*cf.* Botez & Barbeau 1971). Such stimulation may produce either arrest of speech or an uncontrollably rapid rate (*cf.* Guiot *et. al.* 1961).

SPEECH MECHANISMS AND THETA RHYTHM

Botez & Barbeau (1971) call attention to two specific mechanisms underlying speech and language. First there is the starting mechanism, primarily concerned with the initiation of speech movements and with the control of speech volume, pitch changes and articulatory movements. Secondly there is the conceptual system, which is especially concerned with the concepts of words and symbols, and of matching the sensory input to the right word. The final matching and understanding of a spoken message, or the formation of new motor patterns for speech transmission, both involve the recall of memory traces. Botez & Barbeau note that both processes are probably accomplished through cortico-thalamo-cortical circuits under the influence

of basic attention and activity control mechanisms from the brain stem and basal nuclei.

Hippocampal output during theta rhythm was shown by Parmeggiani & Rapisarda (1969) to consistently influence the bioelectric activity of the neocortex, and particularly the responsiveness of the primary auditory and visual areas. I would like briefly to mention the frequency selectivity to theta waves of the nucleus anterior medialis of the thalamus, discovered by Parmeggiani *et. al.* (1974). The resonance is optimum for input volleys of 7 per second, indicating that the nucleus anterior medialis acts as a filter which limits the impulse rate of theta volleys to below roughly 8 per second. This process has been proposed by Parmeggiani and his co-workers as a gate which is open or closed depending on the intensity and frequency of hippocampal output volleys and can therefore control the integration of archicortical and neocortical activities.

KLAUDER'S PHENOMENON

Biological systems are invariably non-linear and the introduction of functional polynomial series representations to linear systems theory has meant that a large class of non-linear systems have come within its scope, since in many cases it is not the detailed behavior of the individual elements that is of interest but the macroscopic behavior of the system. There are however serious criticisms concerning the validity and range of application of the modern functional approach to biological systems (*cf.* McKean 1972; Palm & Poggio 1977a; 1977b). On the other hand the microscopic equations of motion of matter in principle contain all the information about a system. They cannot generally be solved in practice but nonetheless it is sometimes possible to get an idea of the patterns of events which take place in some specific field, and this can be quite instructive. The structure I have described, albeit crudely, of a speech and memory structure is most charitably represented in terms of traditional field theory and I feel that John Klauder has made an approach to field theory which may account for certain of its key aspects.

Klauder utilizes the term "shot noise" in the sense of Rice (1945) mentioned earlier, to signify a grouping together of unitary noises. The "1/f-like" content is uncertain but ubiquitous and while Klauder has not actively investigated "1/f-like" noises, he is aware of and intrigued by their widespread occurrence. Such behavior for the power spectrum, Klauder feels, must arise as some sort of fixed point, limited scaling behavior in the presence of a wide class of weak non-linearities that invariably exist in nature.

Klauder had been examining problems associated with quantum field theory for a number of years when he discovered an effect referred to as Klauder's Phenomenon (*cf.* Klauder 1973a; 1973b). This effect is discussed by Simon (1973) and by DeFacio & Hammer (1974); the latter with the expressed intention of making the mathematical presentation more easily accessible to working physicists and others. In essence Klauder's phenomenon signifies that a nonrenormalizable interaction, as defined in conventional perturbation theory, cannot be completely turned off once it has been turned on (*cf.* Ezawa *et. al.* 1974). As the coupling constant tends to zero ($\lambda \downarrow 0$), a nonrenormalizable interaction converges instead to a pseudo-free theory that is fundamentally different from a free theory.

THE "SHOT NOISE" CASE

Klauder stresses that the problems encountered in studies of specific covariant quantum field models are sufficiently complicated that study of analagous problems in alternative models can be of considerable value. It was in this spirit that he examined the path space quantization of a class of examoles more appropriate to noise theory (*cf.* Klauder 1975b). An example of this kind, in which the generalized types of histories may not be pointwise defined, is illustrated in Klauder (1975a; 1978). The behavior is conceptually and formally the same as that encountered in the anharmonic oscillator, although the hard-core behavior is much more complex. Various categories of continuous and discontinuous perturbation behavior are obtained by varying just two parameters. One parameter (ε) controls the roughness of paths in the free theory, while a second parameter (ρ) controls the singularity sensitivity of the interaction.

Path histories in the free theory, including possible Gaussian and Poisson contributions, are at their maximum roughness when the sensitivity of the interaction term is at its greatest. In this condition the free theory is realized as white noise while, on the other hand, every interacting theory is realized as various forms of "shot noise" (*cf.* Rice 1945). In particular, when the coupling constant tends to zero ($\lambda \downarrow 0$), the interaction does not pass to the white noise of the free theory, but passes instead to a pseudo-free theory still based on "shot noise". In other words a certain form of "shot noise", and not just white noise, or filtered white noise, is relevant as a zero-coupling limit. Klauder emphasizes the disconnection between the free and the pseudo-free theories by pointing out that the white noise measure is concentrated on distributional derivatives of continuous paths which have unbounded variation, while the "shot noise" measure on the other hand, is concentrated on distributional derivatives of paths of bounded

variations which are not continuous.

CONCLUDING REMARKS

A "1/f-like" spectrum for loudness fluctuations of speech infers particular kinds of constraints on the growth and decay of spectral energies associated with individual elements within any ensemble. This implies that the coherence underlying language organization depends on a continuing statistical description of any ensemble pattern of speech. Comparable remarks appear applicable also to memory.

The art it seems, is to be able to make use of the attentional processes to control arousal, which can be applied over many time scales in a loosely linked relation to cycles of theta rhythm. Knox & Braminder (1977) proposed that a difference between subjective time and mechanically measured time is almost certainly an indication that a message is being competently transmitted and understood. Such a difference would signify a high likelihood of direct correlation between the relation of subjective and mechanically measured time, with what is known as a subject's "tactics of attention". It seems intuitively reasonable to assume that the esthetics of communication are to be discovered in the efficiency of communication brought about by this method of focusing, which is the subjective time experience.

Expressed in terms of attention and arousal, the two variables described by Klauder for the "shot noise" case become the dynamic of temporal focusing ($\mathcal{E}$) and the singularity sensitivity to fluctuation interactions (ρ). The detailed functioning of a perceptual system structured according to variables such as those described by Klauder can be understood only approximately, as also indeed can intelligent behavior. But as long as the process of cognition deals only with the outcomes of changes in the central nervous system, it becomes possible to at least conceive of creative thought along the lines suggested by Donald Campbell's term, "variation and selective retention" (*cf.* Campbell 1974; 1977). My own feeling is that an approximation must necessarily be accepted at some level.

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